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Oscillatory MHD Free Convective Flow and Mass transfer through Porous Medium bounded by a Vertical Porous Channel with Thermal Source and Slip Boundary Conditions

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Abstract : Oscillatory MHD free convective flow and mass transfer flow of a viscous incompressible electrically conducting fluid through a porous medium bounded by two infinite vertical parallel porous plates under slip boundary conditions in the presence of heat source is investigated . The two porous plates are subjected to a constant injection and suction velocity, respectively. The pressure gradient in the channel oscillates periodically with time. The temperature difference of the two plates is assumed high enough to induce heat transfer due to radiation. The governing equations are solved analytically adopting complex variable notations for velocity, temperature and mass concentration of the fluid. The analytical results are evaluated numerically and then presented graphically to illustrate the influence of physical parameters. Numerical values of the skin - friction coefficient, Nusselt number and Sherwood number are presented through tables and discussed numerically.

Key words : MHD, Thermal source, velocity slip, mass transfer, porous medium

Introduction

The phenomenon of free convection arises in fluid when temperature changes cause density variation leading to buoyancy forces acting on the fluid elements. It can be observed in our daily life in atmospheric flow, which is driven by temperature differences. Free convective flow past a vertical plate was studied extensively by Ostrach (1952, 1953) and many other researchers. Channel flows through porous medium have varied applications in the field of chemical engineering, agriculture engineering and petroleum technology. In some applications e.g. in microfluidic and nanofluidic device where the surface to volume ratio is large , the slip behavior is more typical and slip boundary condition is usually used for the velocity field . Tao (1960) reported on combined free and forced convections in channels. Sinha (1969) studied fully developed laminar free convection flow between vertical parallel plates. Soundalgekar (1970) considered hydromagnetic fluctuating flow past an infinite porous plate in slip flow regime. Magnetogasdynamics flow past an infinite porous plate in slip flow regime was investigated by Sastry and Bhadram (1976). Raptis and Peridiks (1985) studied the unsteady free convection flow through a highly porous medium bounded by an infinite porous plate. Singh (1988) investigated natural convection in unsteady Couette motion. Zaturska et al. (1998) reported on the flow of a viscous fluid driven along a channel by suction at porous walls. Barletta (1998) investigated laminar mixed convection with viscous dissipation in a vertical channel.Unsteady MHD convective heat transfer past a semi infinite vertical porous plate with variable suction was presented by Kim (2000). Kamel (2001) discussed unsteady MHD convection through porous medium with combined heat and mass transfer with heat source / sink. Din (2003) reported effect of thermal and mass buoyancy forces on the development of laminar mixed convection between vertical parallel plates with uniform wall heat and mass fluxes. Magnetohydrodynamic mixed convection in a vertical channel was studied by Umavathi and Malashetty (2005). Makinde and Osalusi (2006) considered MHD steady flow in a channel with slip at the permeable boundaries. Unsteady MHD free convective flow and heat transfer along a vertical porous plate with variable suction and internal heat generation was investigated by Sharma and Singh (2008). Zanchini (2008) presented mixed convection with variable viscosity in a vertical annulus with uniform wall temperature. Sharma et al. (2009) observed radiation effects on unsteady MHD free convective flow with Hall current and mass transfer through viscous incompressible fluid past a vertical porous plate immersed in porous medium with heat source / sink. Free convective flow of heat generating / absorbing fluid between vertical porous plates with periodic heat input was studied by Jha and Ajibade (2009). Sharma and Mehta (2009) investigated MHD Unsteady slip flow and heat transfer in a channel with slip at the permeable boundaries. Unsteady MHD convective flow within a parallel plate rotating channel with thermal source / sink in a porous medium under slip boundary conditions was studied by Seth et al. (2010). Sharma et al. (2010) presented unsteady MHD free convective flow and heat transfer between heated inclined plates with magnetic field in the presence of radian effects.The effects of slip condition transverse magnetic field and radiative heat transfer to unsteady flow of a conducting thin fluid through a channel was discussed by Hamza et al. (2011).Khem Chand and Sapna (2012) studied hydromagnetic free convective oscillatory Couette flow through a porous vertical channel with periodic wall temperature. Singh (2012) reported solution of MHD oscillatory convection flow through porous medium in a vertical porous channel in slip-flow regime. Effect of volumetric heat generation / absorption on convective heat and mass transfer in porous medium in between two vertical plates was investigated by Sharma and Dadheech (2012). Kesavaiah et al. (2013) observed effects of radiation and free convection currents on unsteady Couette flow between two vertical parallel plates with constant heat flux and heat source through porous medium. Analysis of MHD convective flow along a moving semi-vertical plate with internal heat generation was presented by Sharma and Yadav (2014).

Aim of the present paper is to analyze oscillatory MHD free convective flow and mass transfer through the porous medium bounded by two infinite vertical porous plates with hydrodynamic slip boundary conditions and temperature dependent thermal source/sink subjected to constant injection and the same constant suction velocities.

Formulation of the Problem

Consider oscillatory MHD convective flow of a viscous incompressible and electrically conducting fluid through porous medium filled in a vertical channel. The two porous plates of the vertical channel are at distance h apart. A Cartesian coordinate system is introduced such that the x^*-axis lies vertically upwards direction along one of the plate and y^*-axis is perpendicular to the parallel plates. It is assumed that two infinite vertical parallel plates of the channel are permeable with hydrodynamic slip boundary conditions with constant injection velocity through the porous plate at y^* =0 and simultaneously withdrawn with the same rate of suction velocity through the other plate at y^* =h. The temperature of the plate at y^* =0 is assumed to oscillates periodically with time. All fluid properties are assumed to be constant except the density in terms of thermal and concentration buoyancy effects. The flow is considered to be fully developed laminar and oscillatory. The pressure gradient in the channel assumed to oscillates periodically with time. It is assumed that a magnetic field of uniform strength B_0 is applied perpendicular to the plates of the channel. The magnetic Reynolds number is taken to be small enough so that the induced magnetic field is neglected. Hall effect, electrical and polarization effects are also negligible. The temperature difference of the two plates is assumed to be high enough to induce heat transfer due to radiation. The fluid is assumed to be optically thin with relatively low density.

With above assumptions and usual Boussinesq approximation, the governing boundary layer equations for mass, momentum, energy and species conservations are given by

$$\frac{\partial v^*}{\partial y^*} = 0 \quad \Rightarrow \quad v^* = V, \qquad \ldots(1)$$

$$\frac{\partial u^*}{\partial t^*} + V\frac{\partial u^*}{\partial y^*} = -\frac{1}{\rho}\frac{\partial p^*}{\partial x^*} + \upsilon\frac{\partial^2 u^*}{\partial y^{*2}} + g\beta T^* + g\beta^* C^* - \frac{\upsilon}{K^*}u^* - \frac{\sigma B_0^{\,2}}{\rho}u^*, \qquad \ldots(2)$$

$$\frac{\partial T^*}{\partial t^*} + V\frac{\partial T^*}{\partial y^*} = \frac{\kappa}{\rho C_p}\frac{\partial^2 T^*}{\partial y^{*2}} - \frac{1}{\rho C_p}\frac{\partial q^*}{\partial y^*} + \frac{Q}{\rho C_p}T^*, \qquad \ldots(3)$$

$$\frac{\partial C^*}{\partial t^*} + V\frac{\partial C^*}{\partial y^*} = D\frac{\partial^2 C^*}{\partial y^{*2}}, \qquad \ldots(4)$$

where u^* *is the* velocity component in x^* -direction, V the constant injection / suction velocity, t^* the time , p^* the fluid pressure , ρ the fluid density, g the acceleration due to gravity , β and β^* are the thermal and concentration expansion coefficients respectively, K^* the permeability of the porous medium, T^* the temperature of the fluid , C^* the species concentration in the fluid , υ the Kinemetic viscosity of the fluid, σ the electrial conductivity of the fluid , B_0 the magnetic induction

, κ the thermal conductivity , C_p the specific heat at constant pressure , q^* the radiative heat flux , Q the volumetric rate of heat generation / absorption and D the mass diffusion coefficient.

The corresponding boundary conditions are

$$y^* = 0: \quad u^* = L_1 \frac{\partial u^*}{\partial y^*}, \quad T^* = T_0 e^{i\omega^* t^*}, \quad C^* = C_w e^{i\omega^* t^*};$$

$$y^* = h: \quad u^* = L_2 \frac{\partial u^*}{\partial y^*}, \quad T^* = 0, \quad C^* = C_w e^{i\omega^* t^*}, \qquad \text{...(5)}$$

Where ω^* is the frequency of the oscillation, $L_1 = (\frac{2-r_1}{r_1})L$ and $L_2 = (\frac{2-r_2}{r_2})L$, L being mean free path and r_1 and r_2 are the Maxwell's reflexion coefficient , T_0 is the mean temperature at the wall and C_w is the mean concentration near the walls .

Following Cogley et al. (1968), it is assumed that the fluid is optically thin with relatively low density and the radiative heat flux is given by

$$\frac{\partial q^*}{\partial y^*} = 4\alpha^2 T^*, \qquad \text{…(6)}$$

where α is the mean radiation absorption coefficient.

Method of Solution

Introducing the following dimensionless quantities

$$x = \frac{x^*}{h}, \quad y = \frac{y^*}{h}, \quad u = \frac{u^*}{V}, \quad T = \frac{T^*}{T_0}, \quad t = \omega^* t^*,$$

$$\omega = \frac{\omega^* h^2}{\upsilon}, \quad p = \frac{p^*}{\rho V^2}, C = \frac{C^*}{C_w}, \quad \mathrm{Re} = \frac{Vh}{\upsilon},$$

$$Gr = \frac{g\beta T_0 h^2}{V\upsilon}, \quad Gm = \frac{g\beta^* h^2 C_w}{V\upsilon}, \quad M^2 = \frac{\sigma B_0 h^2}{\upsilon\rho},$$

$$K = \frac{K^*}{h^2}, \quad \mathrm{Pr} = \frac{\mu C_p}{\kappa}, \quad N^2 = \frac{4\alpha^2 h^2}{\kappa},$$

$$S = \frac{Qh^2}{\kappa}, \gamma_1 = \frac{L_1}{h}, \quad \gamma_2 = \frac{L_2}{h}, \qquad \text{...(7)}$$

into the equations (2) to (4) with equation (6) , we get

$$\omega \frac{\partial u}{\partial t} + \mathrm{Re}\frac{\partial u}{\partial y} = -\mathrm{Re}\frac{\partial p}{\partial x} + \frac{\partial^2 u}{\partial y^2} + GrT + GmC - \left(M^2 + \frac{1}{K}\right)u \qquad \text{...(8)}$$

$$\omega \frac{\partial T}{\partial t} + \mathrm{Re}\frac{\partial T}{\partial y} = \frac{1}{\mathrm{Pr}}\frac{\partial^2 T}{\partial y^2} - \frac{N^2}{\mathrm{Pr}}T + \frac{S}{\mathrm{Pr}}T \qquad \text{…(9)}$$

$$\omega \frac{\partial C}{\partial t} + \mathrm{Re}\frac{\partial C}{\partial y} = \frac{1}{Sc}\frac{\partial^2 C}{\partial y^2} \qquad \text{…(10)}$$

where Gr the Grashof number, Gm the modified Grashof number, M the Hartmann number, K the permeability parameter, Re the cross flow Reynolds number, Pr the Prandtl number , N the radiation parameter and Sc the Schmidt number .

The corresponding dimensionless boundary conditions are

$$y = 0: \quad u = \gamma_1 \frac{\partial u}{\partial y}, \quad T = e^{it}, \quad C = e^{it};$$

$$y = 1: \quad u = \gamma_2 \frac{\partial u}{\partial y}, \quad T = 0, \quad C = e^{it}. \qquad \text{…(11)}$$

where γ_1 and γ_2 are slip –flow parameters. Equations (8) to (10) are coupled, non –linear second order partial differential equations and can not be solved in closed form. Assuming the solution in complex variable notations for unsteady periodic flow in the porous channel when the fluid is also acted upon by a periodic drop in pressure, as

$$u(y,t) = u_0(y)e^{it},$$

$$T(y,t) = \theta_0(y)e^{it},$$

$$C(y,t) = C_0(y)e^{it},$$

$$-\frac{\partial p}{\partial x} = Pe^{it}, \qquad \ldots(12)$$

where P is a constant.

Substituting (12) into equations (8) to (10), we obtain

$$u_0'' - \mathrm{Re}\,u_0' - (M^2 + \frac{1}{K} + i\omega)u_0 = -\mathrm{Re}\,P - Gr\theta_0 - GmC_0, \qquad \ldots(13)$$

$$\theta_0'' - \mathrm{Re}\,\mathrm{Pr}\,\theta_0' - (N^2 - S + i\omega\,\mathrm{Pr})\theta_0 = 0, \qquad \ldots(14)$$

$$C_0'' - \mathrm{Re}\,ScC_0' - i\omega ScC_0 = 0, \qquad \ldots(15)$$

where prime denotes ordinary differentiation with respect to y.

The corresponding boundary conditions are given by

$$y = 0:\; u_0 = \gamma_1 \frac{du_0}{dy},\; \theta_0 = 1,\; \mathrm{C}_0 = 1;$$

$$y = 1:\; u_0 = \gamma_2 \frac{du_0}{dy},\; \theta_0 = 0,\; \mathrm{C}_0 = 1. \qquad \ldots(16)$$

Equations (13) to (15) are ordinary second order coupled differential equations and solved under the boundary conditions (16).

Through straight forward calculations, solutions of u_0, θ_0 and C_0 are known. Finally the expressions of $u(y,t)$, $T(y,t)$ and $C(y,t)$ are known and given by

$$u(y,t) = \begin{pmatrix} A_5e^{m_5y} + A_6e^{m_6y} + A_7 + A_8e^{m_3y} \\ +A_9e^{m_4y} + A_{10}e^{m_1y} + A_{11}e^{m_2y} \end{pmatrix} e^{it}, \qquad \ldots(17)$$

$$T(y,t) = \left(A_3e^{m_3y} + A_4e^{m_4y}\right)e^{it}, \qquad \ldots(18)$$

$$C(y,t) = \left(A_1e^{m_1y} + A_2e^{m_2y}\right)e^{it}, \qquad \ldots(19)$$

where $A_1\; to\; A_{11}\; and\; m_1\; to\; m_6$ are constants and their expressions are not presented here for the sake of brevity.

Skin Friction Coefficient

The skin friction coefficient at the plates $y = 0$ and $y = 1$ are respectively given by

$$C_{f_0} = \frac{\tau_{w_0}}{\rho V^2} = \frac{1}{\mathrm{Re}}(\frac{\partial u}{\partial y})_{y=0} = A_{12}e^{it}; \qquad \ldots(20)$$

$$where \quad \tau_{w_0} = \mu(\frac{\partial u^*}{\partial y^*})_{y^*=0}$$

$$C_{f_1} = \frac{\tau_{w_1}}{\rho V^2} = \frac{1}{\mathrm{Re}}(\frac{\partial u}{\partial y})_{y=1} = A_{13}e^{it}; \qquad \ldots(21)$$

$$where \quad \tau_{w_1} = u(\frac{\partial u^*}{\partial y^*})_{y^*=h}$$

Nusselt Number

The rate of heat transfer in terms of Nusselt number at the plates $y = 0$ and $y = 1$ are respectively given by

$$Nu_0 = \frac{q_{w_0}\nu}{\kappa VT_0} = -\frac{1}{\mathrm{Re}}(\frac{\partial T}{\partial y})_{y=0} = A_{14}e^{it}; \qquad \ldots(22)$$

where $q_{w_0} = -\kappa(\frac{\partial T^*}{\partial y^*})_{y^*=0}$

$$Nu_1 = \frac{q_{w_1}\nu}{\kappa V T_0} = -\frac{1}{\mathrm{Re}}\left(\frac{\partial T}{\partial y}\right)_{y=1} = A_{15}e^{it}; \quad ...(23)$$

$$where \quad q_{w_1} = -\kappa\left(\frac{\partial T^*}{\partial y^*}\right)_{y^*=h}$$

Sherwood Number

The rate of mass transfer coefficient in terms of Sherwood number at the plates $y=0$ and $y=1$ are respectively given by:-

$$Sh_0 = \frac{m_{w_0}\upsilon}{DVC_w} = -\frac{1}{\mathrm{Re}}\left(\frac{\partial C}{\partial y}\right)_{y=0} = A_{16}e^{it};$$
$$where \; m_{w_0} = -D\left(\frac{\partial C^*}{\partial y^*}\right)_{y^*=0}, \quad \ldots(24)$$

$$Sh_1 = \frac{m_{w_1}\upsilon}{DVC_w} = -\frac{1}{\mathrm{Re}}\left(\frac{\partial C}{\partial y}\right)_{y=1} = A_{17}e^{it};$$
$$where \; m_{w_1} = -D\left(\frac{\partial C^*}{\partial y^*}\right)_{y^*=h}, \quad \ldots(25)$$

The expressions of constants A_{12} to A_{17} are presented through Appendix- A.

Results and Discussion

In order to get physical insight into the problem the numerical calculations for velocity distribution, temperature distribution, species concentration distribution, skin-friction coefficient, rate of heat transfer in terms of Nusselt number and rate of mass transfer in terms Sherwood number are obtained for different values of the physical parameters and demonstrated through graphs and tables. For numerical calculations, ω is valued as 5, t is valued as $\pi/3$ and P is valued as 5.

Figure 1 illustrates that fluid velocity increases due to increase in Grashof number or modified Grashof number, while it decreases due to increase in Schmidt number. It is noted from Figure 2 that fluid velocity decreases with the increase in the radiation parameter, while it increases due to increase in permeability parameter. Figure 3 shows that the velocity increases with the increase in cross flow Reynolds number. In Figure3 , curve IV shows velocity profiles for no slip conditions on both plates. It shows that maximum velocity occur at mid of the channel. Curve V represents fluid velocity in channel for no slip condition on the plate at $y=1$. Curve VI shows fluid velocity in channel for no slip condition on the plate at $y=0$. These two curves (V and VI) shows that there is a sharp increase in the fluid velocity occur near the plate with the slip – flow condition, when slip flow parameters increased from 0 to 0.5. Curve VII depicts that increase in slip – flow parameter at the plate $y=0$, increases fluid velocity in the channel. It can be seen from curve VIII that increase in slip – flow parameter at the plate $y=1$, decreases fluid velocity in channel. Figure 4 shows that fluid velocity increases due to increase in heat generation parameter, while it decreases due to increase in Hartmann number, PrandtL number or heat absorption parameter. Curve V shows fluid velocity in channel when magnetic field is absent. Figure 5 reveals that fluid temperature increases due to increase in cross flow Reynolds number, while it decreases due to increase in radiation. Figure 6 illustrates that fluid temperature increases due to increase in heat generation parameter or Prandtl number, whereas it decreases due to heat absorption. Figure 7 shows that concentration profiles increase due to increase in Schmidt number or frequency oscillation. It is seen from figure 7 that near the plate $y=0$, concentration profiles decreases with increase in cross flow Reynolds number ,while near the plate $y=1$, it increases with increase in cross flow Reynolds number and in middle of channel no effect of change in cross flow Reynolds number is accounted. It is observed from Table 1 that skin – friction at both plates of the channel increase due to increase in Garshof number, modified Garshof number, permeability parameter or heat generation parameter, while it decreases due to increase in Reynolds number, Hartmann number, radiation parameter or Schmidt number. Increase in Prandtl number increases skin – friction on plate at $y=0$ but decreases skin – friction on plate $y=1$. Increase in slip - flow parameter at plate $y=0$ decreases skin – friction at plate $y=0$, while it increases skin – friction at plate $y=1$, but increase in slip-flow parameter at plate $y=1$ decreases skin- friction at both plates of the channel. Table 1 shows that Nusselt number on both plates of the channel decreases due to increase in cross flow Reynolds number. Nusselt number at plate $y=0$ decreases and at plate $y=1$ increases due to increase in Prandtl number or heat source parameter. Increase in Radiation parameter, increases Nusselt number at plate $y=0$ and decreases Nusselt number at plate $y=1$. Table 1 depicts that increase in cross flow Reynolds number , increases Sherwood number at plate $y=0$ and decreases Sherwood number at plate $y=1$, whereas Schmidt number gives reverse effect on both plates , respectively.

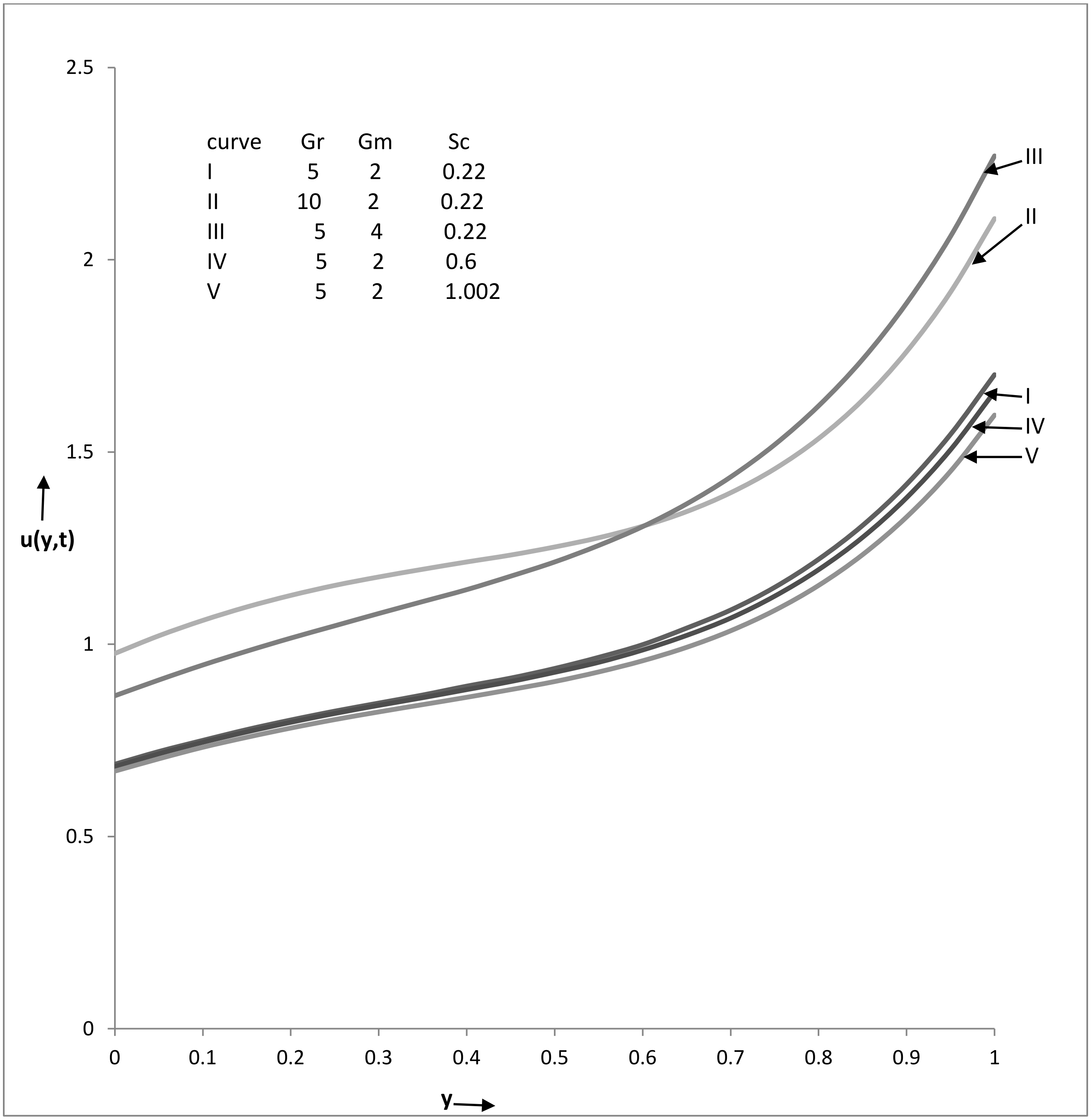

Figure 1. Velocity profiles versus y for different values of Gr, Gm and Sc when $\mathrm{Re}=0.5,\ \omega=5,$ $\mathrm{Pr}=0.71,\ t=\pi/3,\ N=1,\ S=1,\ M=2,\ K=0.5, P=5,\ \gamma_1=1\ and\ \gamma_2=0.5.$

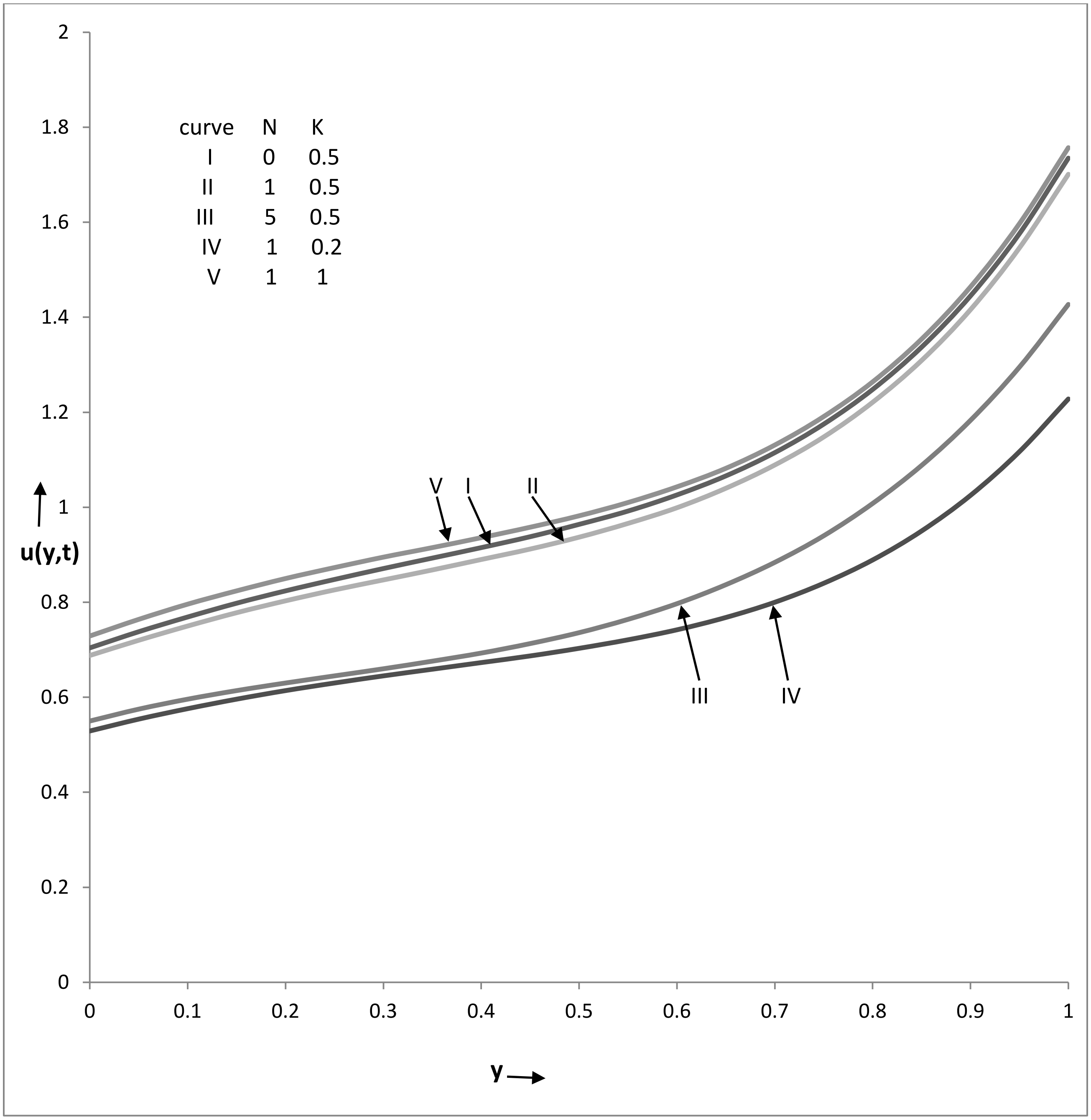

Figure 2. Velocity profiles versus y for different values of N and K when $\mathrm{Re}=0.5,\ \omega=5,\ \mathrm{Pr}=0.71,\ t=\pi/3,\ Sc=0.22,\ S=1,\ M=2,\ Gr=5,\ Gm=2,\ P=5,\ \gamma_1=1\ and\ \gamma_2=0.5.$

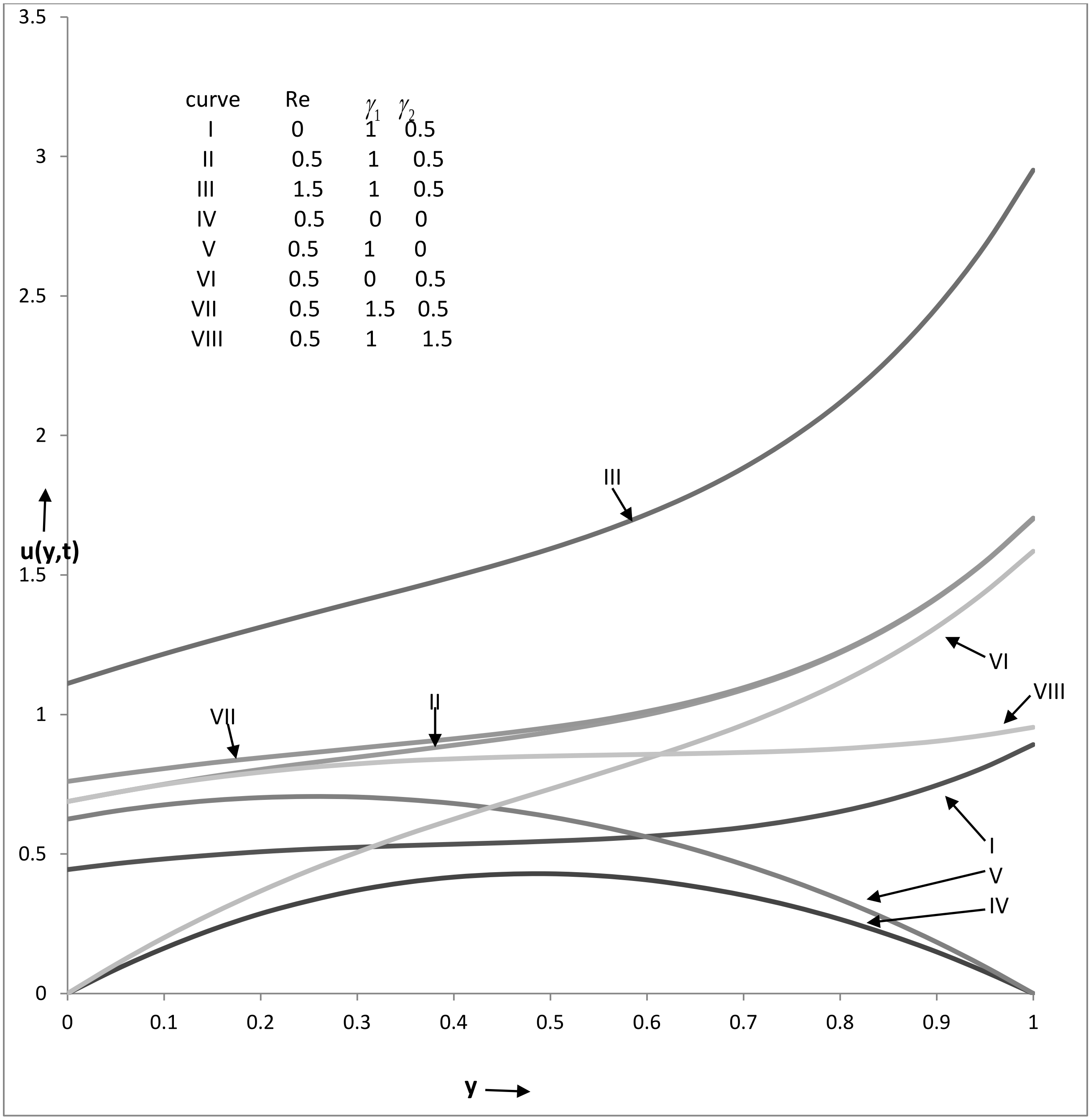

Figure 3. Velocity profiles versus y for different values of Re, γ_1 and γ_2 when $\mathrm{N}=1$, $\omega=5$, $\Pr=0.71$, $t=\pi/3$, $Sc=0.22$, $S=1$, $M=2$, $Gr=5$, $Gm=2$, $P=5$ *and* $K=0.5$.

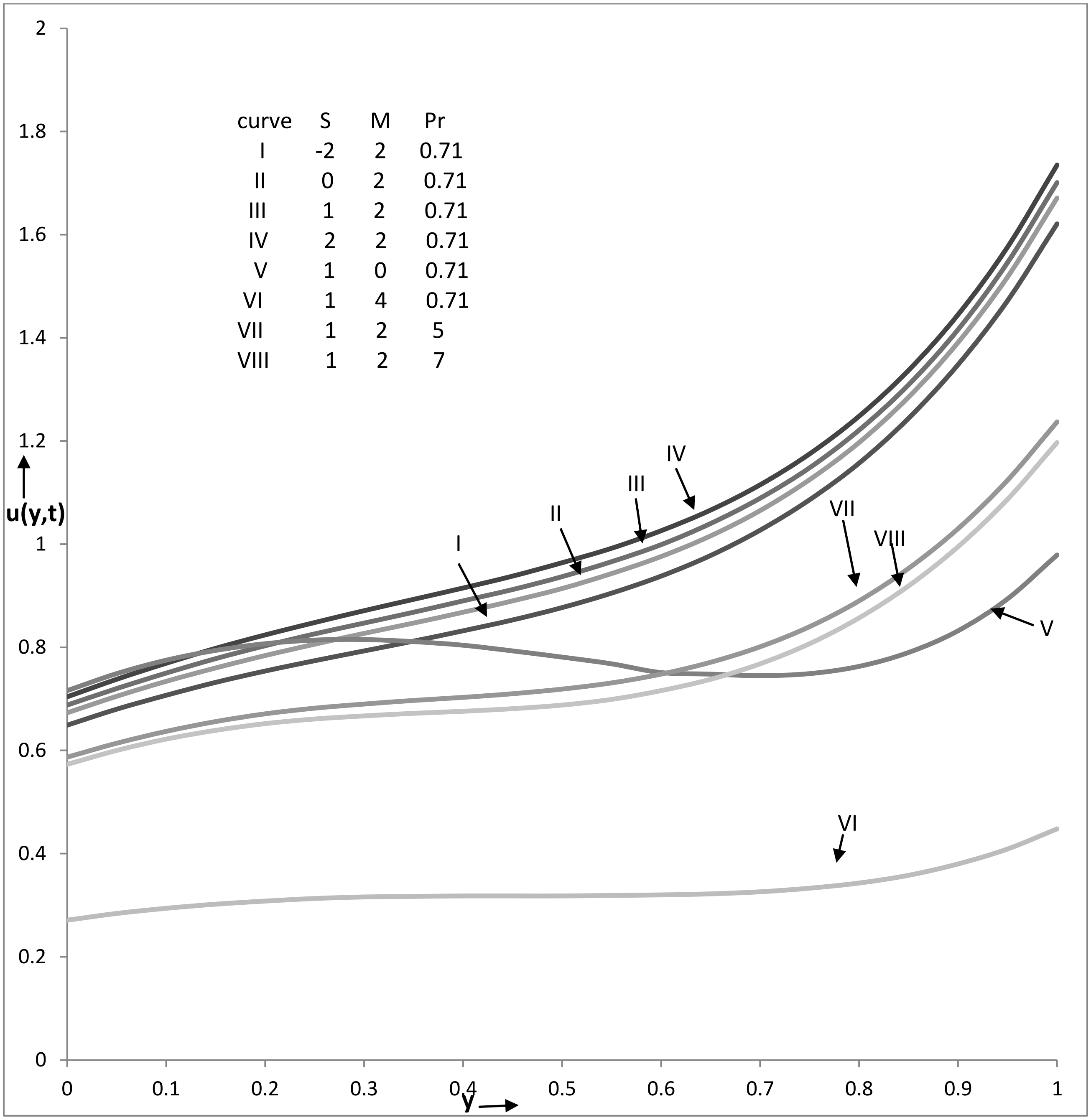

Figure 4. Velocity profiles versus y for different values of S, M and $\Pr$ when $\mathrm{Re}=0.5,\ \omega=5,$ $Gr=5,\ Gm=2,\ Sc=0.22,\ t=\pi/3,\ N=1,\ K=0.5, P=5,\ \gamma_1=1\ and\ \gamma_2=0.5.$

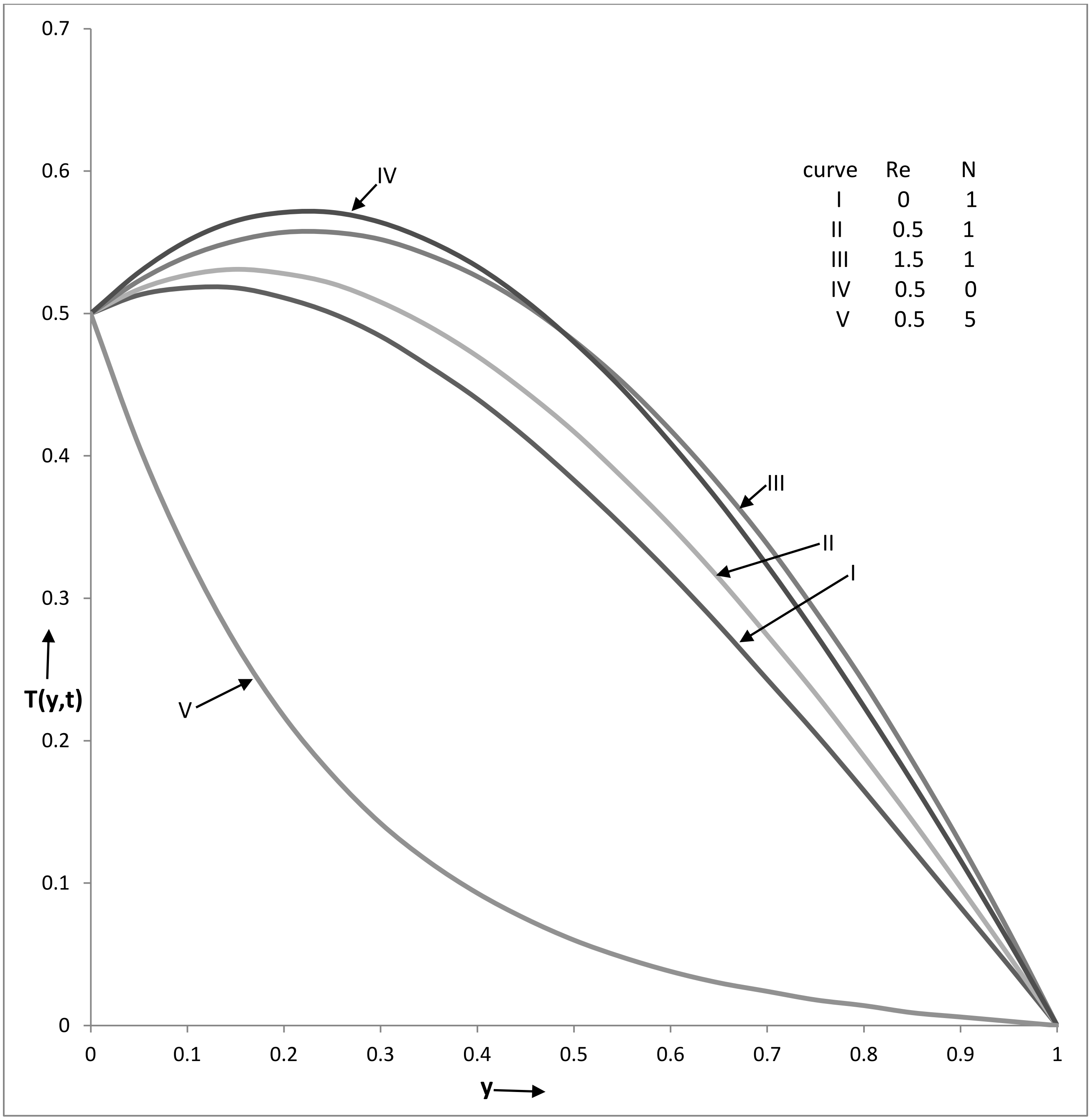

Figure 5. Temperature profiles versus y for different values of Re and N when $K = 0.5,\ \omega = 5,$ $\Pr = 0.71,\ t = \pi/3,\ Sc = 0.22,\ S = 1,\ M = 2,\ Gr = 5,\ Gm = 2,\ P = 5,\ \gamma_1 = 1\ and\ \gamma_2 = 0.5.$

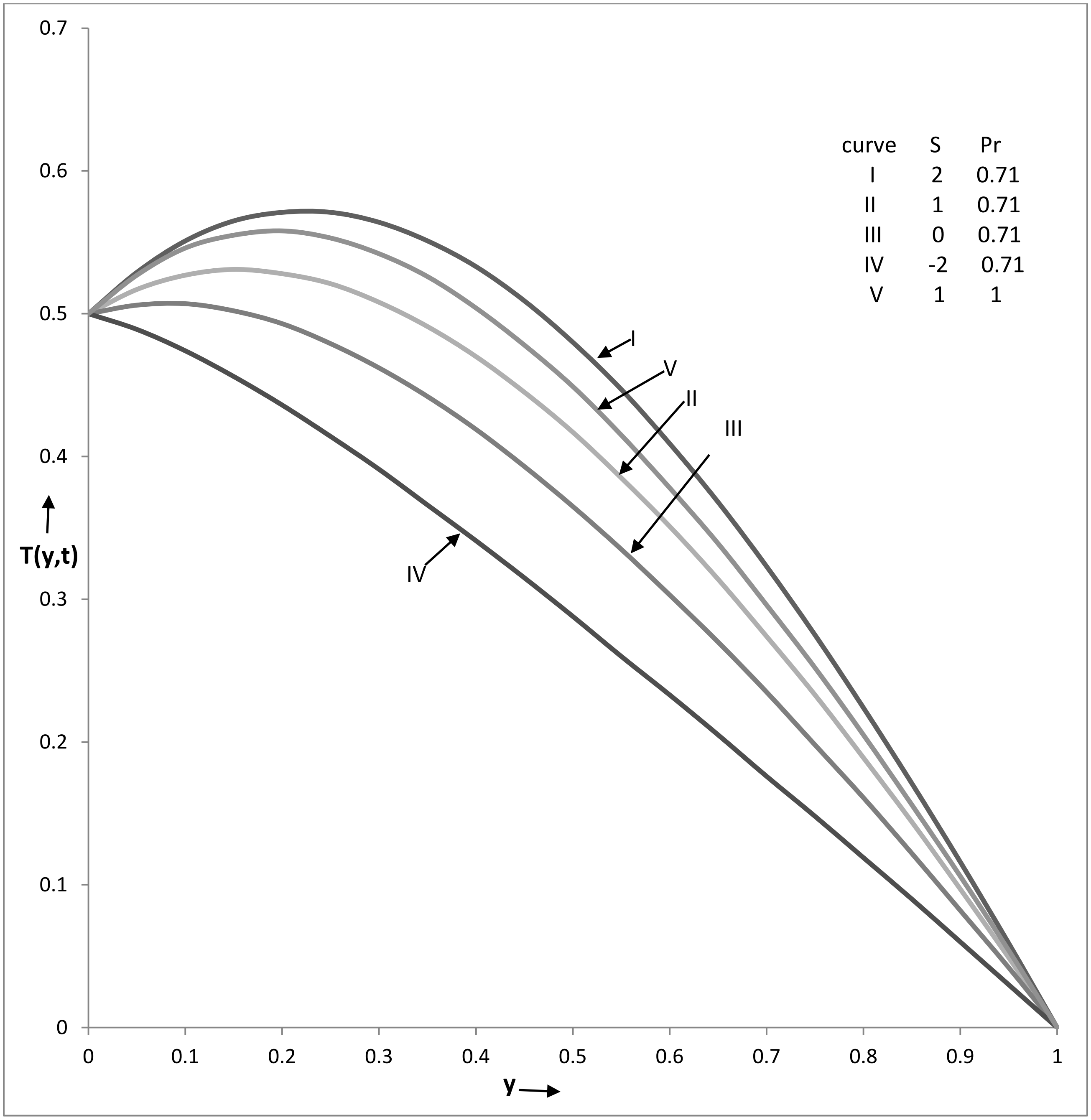

Figure 6. Temperature profiles versus y for different values of S and $\Pr$ when $K = 0.5,\ \omega = 5,$ $\mathrm{Re} = 0.5,\ t = \pi/3,\ Sc = 0.22,\ N = 1,\ M = 2,\ Gr = 5,\ Gm = 2,\ P = 5,\ \gamma_1 = 1\ and\ \gamma_2 = 0.5.$

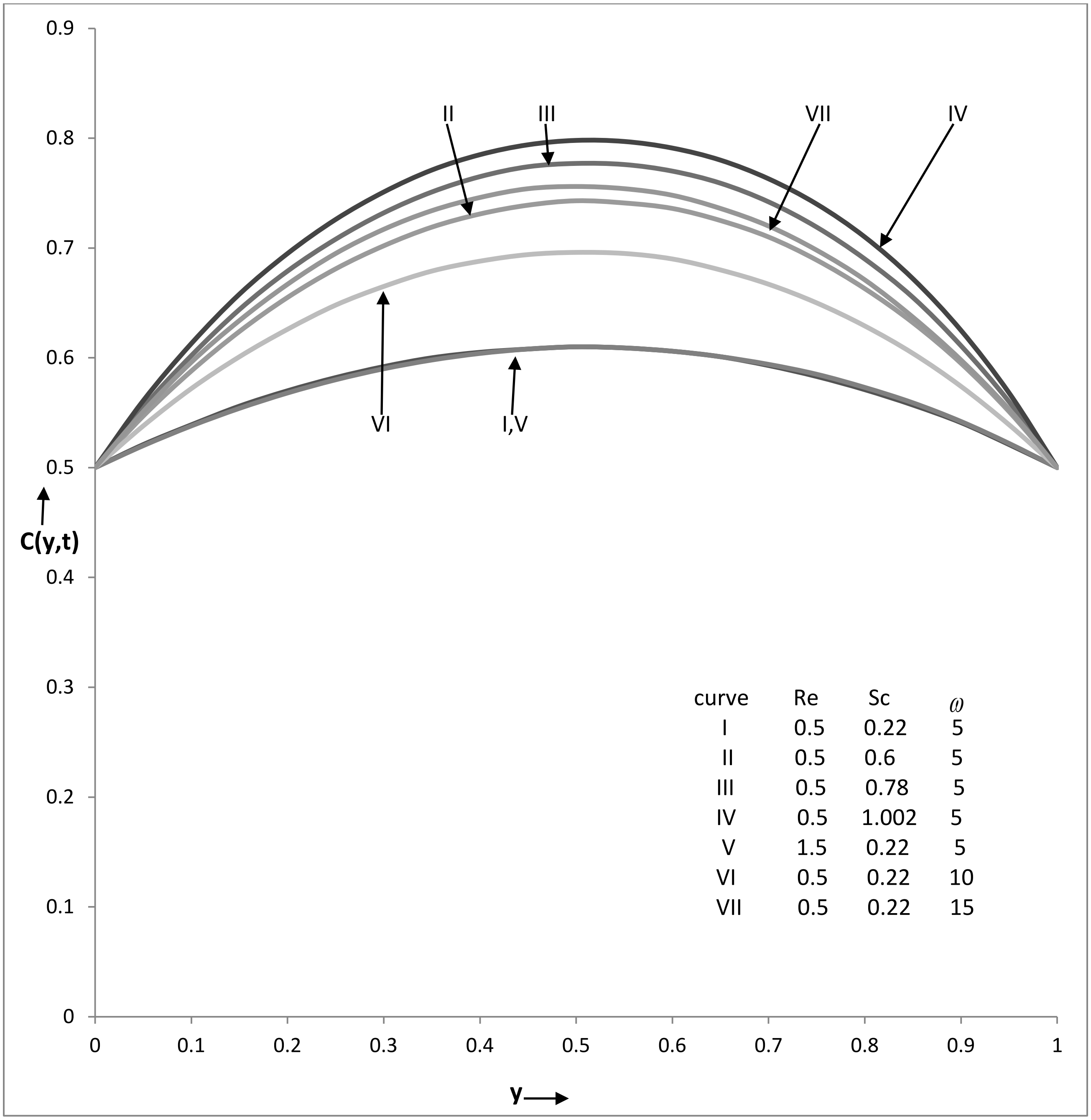

Figure 7. Concentration profiles versus y for different values of Re, Sc and ω when $Gr = 5, Gm = 2$ $\Pr = 0.71, t = \pi/3, N = 1, S = 1, M = 2, K = 0.5, P = 5, \gamma_1 = 1$ *and* $\gamma_2 = 0.5.$

Table 1. Numerical values of skin-friction coefficient , Nusselt number and Sherwood number at the plates for various values of physical parameters

Gr	Gm	Re	M	K	Pr	N	S	Sc	γ_1	γ_2	C_{f_0}	C_{f_1}	Nu_0	Nu_1	Sh_0	Sh_1
5	2	0.5	2	0.5	0.71	3	1	0.22	1	0.5	1.218	6.145	1.697	0.626	-0.877	0.909
10	2	0.5	2	0.5	0.71	3	1	0.22	1	0.5	1.637	7.109	1.697	0.626	-0.877	0.909
5	4	0.5	2	0.5	0.71	3	1	0.22	1	0.5	1.574	8.418	1.697	0.626	-0.877	0.909
5	2	1	2	0.5	0.71	3	1	0.22	1	0.5	0.829	4.395	0.77	0.369	-0.431	0.463
5	2	0.5	4	0.5	0.71	3	1	0.22	1	0.5	0.474	1.551	1.697	0.626	-0.877	0.909
5	2	0.5	2	0.2	0.71	3	1	0.22	1	0.5	0.927	4.339	1.697	0.626	-0.877	0.909
5	2	0.5	2	0.5	1	3	1	0.22	1	0.5	1.221	6.108	1.281	0.726	-0.877	0.909
5	2	0.5	2	0.5	0.71	5	1	0.22	1	0.5	1.1	5.707	4.114	0.125	-0.877	0.909
5	2	0.5	2	0.5	0.71	3	2	0.22	1	0.5	1.231	6.199	1.474	0.709	-0.877	0.909
5	2	0.5	2	0.5	0.71	3	1	0.6	1	0.5	1.208	5.97	1.697	0.626	-1.984	2.17
5	2	0.5	2	0.5	0.71	3	1	1.002	1	0.5	1.183	5.723	1.697	0.626	-2.611	2.967
5	2	0.5	2	0.5	0.71	3	1	0.22	1.5	0.5	0.899	6.162	1.697	0.626	-0.877	0.909

5	2	0.5	2	0.5	0.71	3	1	0.22	1	1.5	1.208	1.115	1.697	0.626	-0.877	0.909

Conclusions

Unsteady MHD free convective flow of a viscous incompressible electrically conducting heat generating / absorbing fluid through porous medium bounded by a vertical channel under slip boundary conditions on both plates is investigated. The significant findings are summarized as given below

(i) Thermal and concentration buoyancy forces, porosity of medium or cross flow Reynolds number accelerate fluid velocity.

(ii) Radiation, magnetic field, Prandtl number or Schmidt number retard fluid velocity.

(iii) Thermal source tends to accelerate fluid velocity, whereas thermal sink has reverse effect on it.

(iv) When channel has no slip condition on both walls, maximum velocity occurs at middle of the channel.

(v) When channel has slip condition on one plate only, fluid velocity increases sharply near the plate with slip flow parameter.

(vi) When slip flow parameter increase at the plate $y=0$, fluid velocity increases in the channel whereas increase in slip flow parameter at plate $y=1$ has reverse effect.

(vii) Cross flow Reynolds number enhances the fluid temperature whereas radiation reduces to it.

(viii) Thermal source or Prandtl number tend to enhance fluid temperature whereas thermal sink has reverse effect on it.

(ix) Increase in Schmidt number or frequency of oscillation, increases concentration profile.

(x) Increase in cross flow Reynolds number increases concentration profiles in half left side of channel, then it decreases concentration profiles in rest part of the channel.

(xi) Thermal and concentration buoyancy effects, porosity of the medium or thermal source increase the skin-friction on both plates.

(xii) Magnetic field, radiation, cross flow Reynolds number or Schmidt number decrease the skin-friction on both the plates.

(xiii) Skin-friction at plate $y=0$ increases, while skin-friction at plate $y=1$ decreases due to increase in Prandtl number but a reverse effect is accounted at both plates of channel due to increase in slip flow parameter at plate $y=0$.

(xiv) Skin-friction at both plates decreases due to increase in slip flow parameter at plate $y=1$.

(xv) Cross flow Reynolds number tends to reduce rate of heat transfer on both plates.

(xvi) Prandtl number or heat source parameter have tendency to reduce rate of heat transfer at plate $y=0$ and to enhance rate of heat transfer at plate $y=1$, but radiation parameter has reverse effect on both the plates respectively.

(xvii) Sherwood number increases at plate $y=0$ and decreases at plate $y=1$ with increase in cross flow Reynolds number but Schmidt number has reverse effect on both plates respectively.

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